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HYDROLOGIC CHANGE IN THE LODDON BASIN: THE INFLUENCE OF GROUNDWATER DYNAMICS ON SURFACE PROCESSES

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ABSTRACT: The late Tertiary Loddon Valley 'deep leads' drainage system passed from the highlands across the Loddon Plains to flow into a Murravian Sea in the far north of the State near the present day Murray River. This ancient drainage channel, now buried sixty metres below the plains, forms the major groundwater path for sub-surface flow from the Central Victorian Highlands. Within the highlands the pressure levels of the Calivil Formation aquifer formed of the deep lead gravels are well below surface level, but become artesian (flowing) in the mid-Loddon Plains. Monitoring of the potentiometric surface over a seven year period indicates that water loss to the surface contributed to present day high salt levels on the Loddon Plain. Rapid rises in pressure levels observed during the two year wet period 1973/74 indicate a high degree of sensitivity of the deep groundwater regime to minor climatic fluctuations. It provides an important clue to the nature of groundwater discharge elsewhere on the plains, and during the well documented phases of high stream flow of late Quaternary times.

INTRODUCTION

The Loddon River drainage basin covers an area of about 15,500 km^2 in northwestern Victoria stretching from the Great Dividing Range to the Murray River. The Loddon is the most westerly of the north flowing streams tributary to the Murray River: for a little less than half its entire length the Murray and its tributaries flow along a valley tract within the highlands. It emerges from the highland front near Bridgewater and thereafter flows as a distributary system across the Loddon Plains, a southwestern part of the more extensive Riverine Plains.

Within the highlands the Loddon Valley is infilled with a thick alluvial sequence. The coarse 'wash', gravels, pebbles and boulders at the base of the alluvium, proved to be one of the richest areas of gold production during the late 19th and early 20th centuries. Geologists of the time established the presence of a late Tertiary 'deep lead' drainage system, ancestor to the present system, but now buried to a depth of more than 100 m. From the outset water within the coarse sediments of the alluvial infill proved a major obstacle to mining, as these gravels provided the major flow paths for groundwater moving plainwards from the Divide. Downstream, beyond the highland front, there was no mining and the course of the valley was lost under the alluvium of the Loddon Plains.

During the drought of 1967-1968, the urgent need to provide good quality water in the northern Victorian shires stimulated investigation of the groundwater potential of the deep lead systems beyond the highlands.

The drilling program commenced in 1968 showed that the Tertiary valley continued across the Loddon Plains as a trench incised into a pre-existing peneplain termed the Mologa Surface. This peneplain is now buried to an average depth of about 70 m, with the ancient river valley incised into it a further 30 m. The average width of the trench is about 5 km.

In the far north of the Loddon Plains, the deep lead system joined a westerly flowing Murray Valley system immediately prior to entering the late Tertiary Murravian Sea (see Fig. 1).

CLIMATE

Rainfall is closely related to topography in the Loddon Drainage Basin. The heaviest rainfall averaging about 1060 mm occurs on the Divide near Lyonville, at the junction of the headwaters of the Lerderderg, Coliban and Loddon Rivers; it decreases to the west to average about 710 mm on

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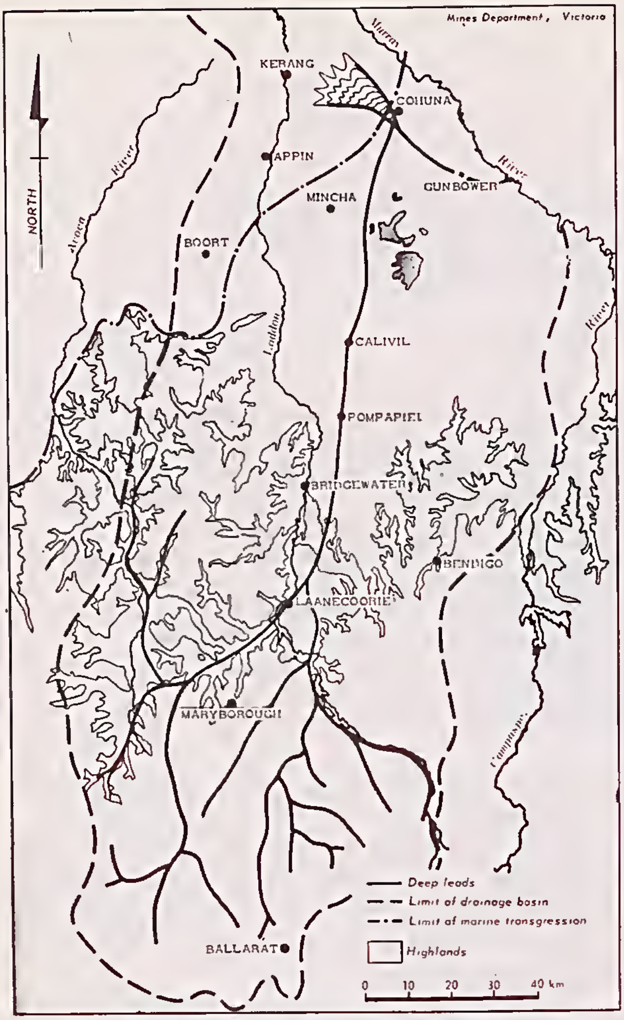

FIG. 1 — Loddon drainage basin — late Tertiary.

the basaltic plateau west of Ballarat. Northwards across the basin there is a steady decline in rainfall such that the Loddon Plains lying roughly between the 350 mm and 450 mm isohyet have a semi-arid climate.

There is a marked incidence of winter rainfall especially in the catchment areas, and at Lyonville the wettest month of June has three times the rainfall of the driest, February. The drier summer period coincides with the time of highest temperature.

Like the isohyets, the isotherms closely relate to the physiography. February is the warmest month, with a mean average value ranging from 18.3°C at Ballarat in the south to 23°C at Kerang in the north. The coolest month is July with mean monthly temperatures ranging from 6.7°C at Ballarat to 8.9°C at Kerang.

GEOLOGY AND STRATIGRAPHY

Mologa Surface

In late Tertiary times, an extensive plain (the Mologa Surface) covered almost the entire area now represented by the Loddon Plains. This was later covered by fluvio-lacustrine and marine deposits; it is now met only in bores at depths from about 60-75 m below the present surface.

In the western parts of the Loddon Plain the Mologa Surface is formed on lower-middle Tertiary carbonaceous Renmark Beds, while in the eastern and southern areas it is developed on deeply weathered Palaeozoic sediments. Extensions of the surface have been traced eastwards of the Terrick Terrick Range and under the western Campaspe Plain. It is considered to be middle Miocene in age.

Loddon Valley Lead

The ancient effluents tributary to the Loddon system commenced near Ballarat, Bullarook, Spring Hill, Creswick, and Lake Learmonth (Hunter 1907). After the confluence of the Bullarook-Mount Prospect Lead and the main Ascot-Clunes Lead in the Parish of Smeaton, the Loddon Valley lead gains substance, and it continues as the trunk Berry-Moolort-Loddon Lead passing northwards through the parishes of Glengower, Redborough, Moolort, Baringhup, Neereman and Laanecoorie. The course passes into the Parish of Woodstock which is the most northerly point where, during the gold mining era, drilling was carried out to determine its true position and character.

The confined Loddon Valley gives way to the Loddon Plains near Bridgewater, and here the trunk lead system emerged from the highlands. A cross-section at Woodstock, about 20 km to the south and still within the highlands shows 103 m of sediment overlying Ordovician basement. A generalized section is:

Depth (m)	*Lithology*	*Stratigraphy*
0- 49.4	clay and sands	Shepparton Formatio
49.4- 87.2 87.2-100.9 100.9-103	coarse sand coarse gravel gravel and pebbles	'Deep Lead' Sediment (Calivil Formation)
103 -105.8	slate (Ordovician)	Basement

The infilled channel is about 1.5 km wide and contains 53.6 m of coarse sand, gravel and pebbles.

In the parish of Bridgewater a section shows the system as a 3.2 km wide valley incised 61 m into a flat Palaeozoic plain, the Mologa Surface, which, as stated, is itself about 60 m below the Loddon Plain. At this point the valley has an asymmetric cross section with an abrupt western boundary and a sloping eastern boundary. Infilling of the valley at Bridgewater shows a similar pattern to that found at Woodstock.

Beyond Bridgewater the buried valley continues northwards through the parishes of Yarraberb, Pompapiel, Calivil, Mologa and Mincha West to join a Murray Valley trunk system in the parish of Gunbower West (Fig. 1). Throughout its length its character is that of a valley incised into a pre-existing peneplain. At Bridgewater and Pompapiel in the south the valley is cut into Palaeozoic sediments but the system then passes onto middle Tertiary carbonaceous sediments. A section at Calivil shows lead gravels occurring from 80-98 m, underlain by 52 m of carbonaceous sands, silts and clays of the Renmark Group. At this point the lead valley is cut 18 m into the Renmark Group which there forms part of the Mologa Surface.

Further north, in the parish of Mologa, the Renmark Group is not present and the valley is again cut in Palaeozoic sediments. At this point the lead sediments are about 15.2 m thick and consist of coarse sands and gravels with minor clay seams. This situation continues into Gunbower West, where a Murray Valley system is met.

Calivil Formation

Beyond Bridgewater the coarse pebbly wash so characteristic of the highland tract rapidly cuts out, to be replaced by gravel and coarse sand. The lithologies persist across the plains. For instance at Calivil, the Mines Department bore (Calivil 2) drilled over the lead has the following lithologies:

Bore Calivil 2

Depth (m)	*Lithology*
0- 51.8	clays with minor shoe-string sands
51.8- 76.8	dense sandy clays
76.4- 95.1	gravels with some minor white clay (Calivil Formation)
95.1-150.3	ligneous sand and clays (Renmark Beds)
150.3	Palaeozoic bedrock

The clean quartz pebbles, gravels and sands so characteristic of the deep leads has been termed the Calivil Formation (Macumber 1973).

Once on the plains there is a gradual thinning of the Calivil Formation from 61 m at Bridgewater to 18 m at Calivil. Beyond Calivil the sequence remains fairly constant, varying from 15-18 m in thickness. The downstream decrease in thickness between Bridgewater and Calivil is seen as the result of a gradually rising marine base level which caused a general upstream movement in the zone of coarse clastic sedimentation (Macumber 1978a). This would also account for the upward fining seen in some sequences.

The gravels and sands are clean throughout the entire length of the system as suggested by their exceptionally high permeabilities measured from Bridgewater in the south to Gunbower in the north (see Table 1). Measurements of the permeablities of the Calivil Formation were carried out at Bridgewater, Calivil, Mincha West and South Cohuna by pump tests using a discharging bore and one or more observation bores. Constant discharge tests were carried out and the results analysed by using the Theis type curves solution for radial flow in an infinite leaky aquifer.

Table 1

Locality	*Transmissivity*
Bridgewater	$5.2 \times 10^3 m^2$/Day
Calivil	$8.9 \times 10^2 m^2$/Day
Gunbower West	$4.3 \times 10^3 m^2$/Day

The hydraulic conductivity at Bridgewater is 85 m/D but falls to 59 m/D at Calivil. Gunbower West is on a Murray Valley system. These values fall within the range given by S. W. Lohman (1967) for coarse gravels, and by Todd (1959) for clean sands, and mixtures of clean sands and gravels.

Although the end of coarse clastic sedimentation is generally sharp, some bores show an upward decrease in grain size of the sequence rather than a sharp change to finer grained sediments, e.g. the Calivil bores, Macorna 2, and Gunbower West 2 bores (Fig. 2). Nevertheless in most instances where this occurs there is still a marked cut-out point for coarse clastic sediments of the Calivil Formation type.

Confining Layers to the Calivil Formation

Between Bridgewater and Pompapiel, the deep trench is totally backfilled by coarse clastic sediments. Overtopping of the trench caused sediment to be deposited on the adjacent peneplain. Having no lateral confinement on this upper surface, the streams fanned out and deposited sediment in an anastomosing distributary pattern.

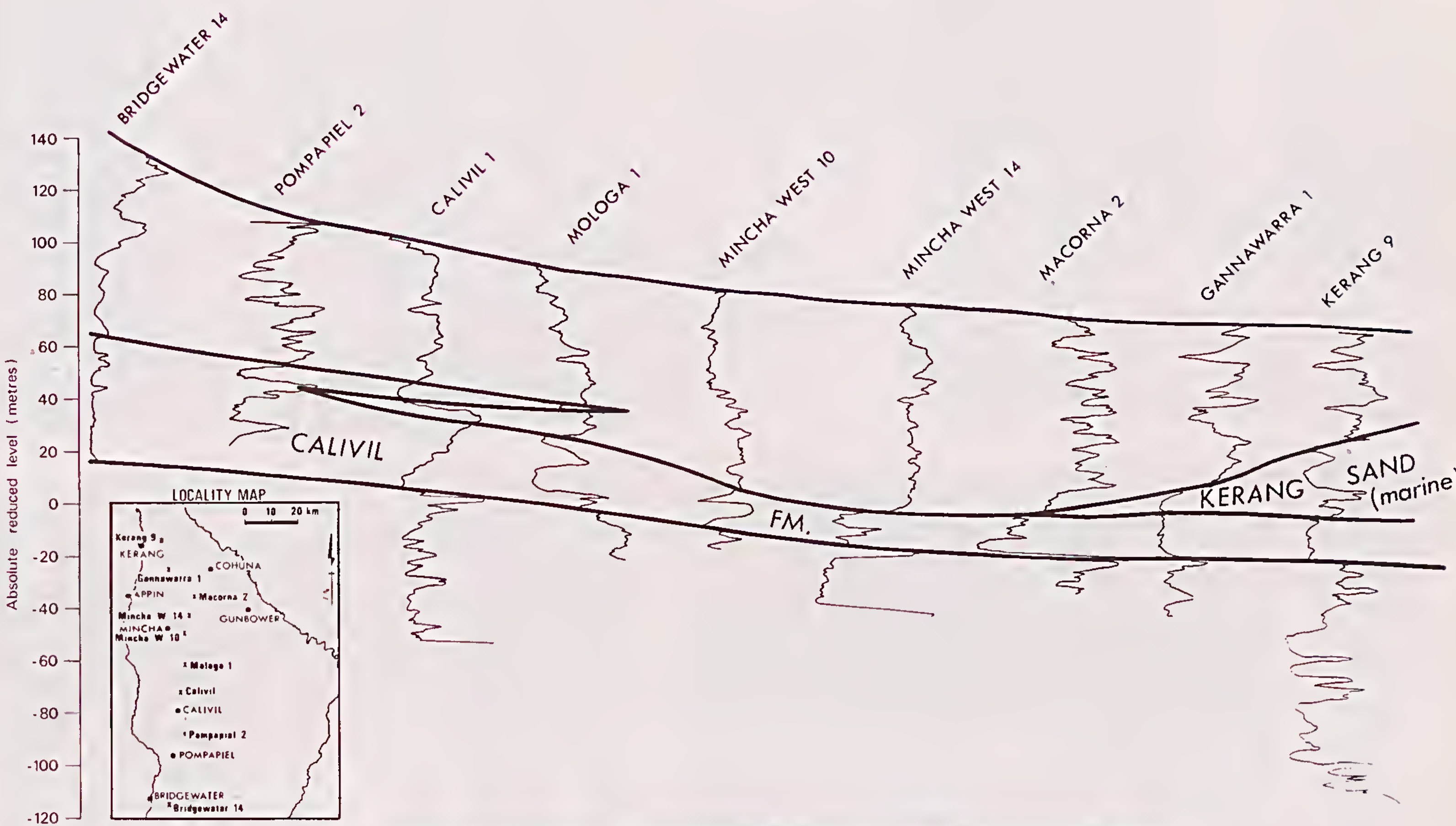

FIG. 2 — Gamma log correlations of the Calivil Formation aquifer down the Loddon Valley.

The channel sediments of these streams are now found over most of the southern plains, as randomly occurring shoe-string sands. Therefore in general bores drilled into the deeper Calivil Formation passing through this zone intersect an overlying major aquifer only when they are drilled over one of the randomly distributed stream channels.

Nevertheless, a sufficient number of bores intersect the aquifers to give rise to a local concept that a 'second stream' exists under the Loddon Plains. The water quality in the upper aquifer is identical with that in the Calivil Formation, with which there is direct aquifer continuity in the southern areas of the plains.

The upper zone of higher permeabilities extends northwards towards Calivil. However, on passing down-basin the top surface of the Calivil Formation falls away with the intervention of a clay wedge which at Calivil is about 15 m thick. Indeed from the central Loddon Plains onwards the deep lead trench is not completely backfilled by coarse sediments: instead the final backfilling is with a dense red and grey mottled clay. This clay forms a virtual valley plug over the Calivil Formation gravels.

With the down-valley increase in thickness and density of the intervening clay wedge there is a concomitant decrease in texture and thickness of the overlying permeable zone, which lenses out after Calivil (Fig. 6). Beyond Calivil the lead gravels are covered by a dense clay aquiclude about 80 m thick.

The effectiveness of the aquiclude therefore differs considerably on passing northwards across the plains. At Bridgewater, a moderately permeable zone extends upwards to within 39 m of the surface. The overlying strata are criss-crossed with shoestring sands, deposited in a fan-head environment where the Loddon River emerges from the highland front. On passing downstream, however, there is a general decrease in grain size as the stream channels give way to a flood-plain environment. In the central-lower Loddon Plains beyond Calivil a clay lithofacies predominates in the sediments confining the Calivil Formation.

HYDROLOGY

Regional Groundwater Flow

The main catchment areas for the Loddon drainage basin lie on the northern slopes of the east-west trending Western Highlands which make up a western physiographic province of the Great Dividing Range in Victoria. The Great Divide in western Victoria is composed predominantly of Palaeozoic rocks and Tertiary basalts. The latter, in general, form little more than a broad flat low divide — the Ballarat Plateau (Thomas 1956). The outpouring of basalts to form the Ballarat Plateau infilled the existing deeply incised late Tertiary valleys, so modifying the drainage system that it led to a major northwards shift in the Tertiary divide. Much of the intervening area which was formerly part of the Loddon drainage basin now drains southwards along the Leigh River and Mt Emu Creek to the Southern Ocean. The surface drainage basin of the Loddon River is today smaller than its late Tertiary 'deep-lead' equivalent. It is also smaller than the present-day groundwater basin which is substantially the same as it was in Tertiary times.

The effect of water table configuration on regional groundwater flow was demonstrated initially by Toth (1962, 1966). In considering the effect in an area of constant gentle regional slope (as occurs in the case of the Loddon Valley) he concluded that, given a homogeneous medium (which is not the case in the Loddon Valley) this groundwater flow is essentially horizontal, with recharge concentrated at the upstream end of the recharge area and discharge at the downstream end. The 'hinge-line' separating the areas is midpoint, except where a major valley is present, and in this instance the recharge covers most of the upland area and discharge is concentrated in the valley. Freeze (1969) concluded that in a simple two layer system in an area of constant regional slope, the hinge line occurs at the midpoint of the basin. With an increase in permeability ratio, aquifer to aquiclude, the hinge line moves upslope; large permeability ratios are conducive to 'large discharge areas in a simple system where a subsurface highway exists' (Freeze 1969, p. 88).

Clearly the Loddon Valley constitutes a regional drainage system containing a dominant aquifer traversing the basin and acting as a highway for groundwater flow.

From an agricultural viewpoint the position of the recharge-discharge boundary is of prime importance, for it marks the point beyond which water entering the ground cannot overcome the upward potential gradient and will be subject to evapotranspiration in the vicinity of its point of entry.

With flowing artesian conditions present in the basal aquifers, the potential is established for upward moving groundwater to prevent deep percolation of infiltrating surface waters. This is most apparent in areas south of Calivil and north of Mincha West where the aquitard is significantly more permeable than in the central Loddon Plain (see Gamma log section, Fig. 2). Nevertheless even where the permeability of the aquitard is lower, the presence of flowing artesian conditions will still prevent deep percolation. However with a low permeability aquitard, the rate of upward vertical movement is also correspondingly diminished.

The problems inherent in the large scale flood irrigation of a discharge area are quite obvious. They include waterlogging, increased soil salinities in semi-arid environments resulting from evaporation of irrigation water remaining in the near surface zones, and destruction of vegetation including plants previously evapotranspiring shallow groundwater and thereby suppressing the water table.

Such problems rapidly developed on the Loddon Plains following the introduction of large scale flood irrigation late last century. After only nineteen years, the rising water tables caused severe waterlogging and soil salinization. Many formerly dry lake systems are now either ephemeral or permanent lakes. At present about one third of the district is severely salt affected and virtually the whole of the central and lower Loddon Plains has a water table at less than 2 m (Fig. 3). The immediate cause of salinization is, clearly, the increased water budget following the introduction of irrigation practice. However while the heavy soils of the Kerang Region hinder the deep percolation of infiltrating surface waters, the upward pressure gradients in the groundwater systems prevent any downward percolation. This has led to a rapid rise in water tables, with the irrigation water a significantly greater contributor to the overall water budget than the groundwater system, which acts largely as a hydrostatic barrier to drainage into the deeper strata.

The Loddon Plains beyond Calivil, where the

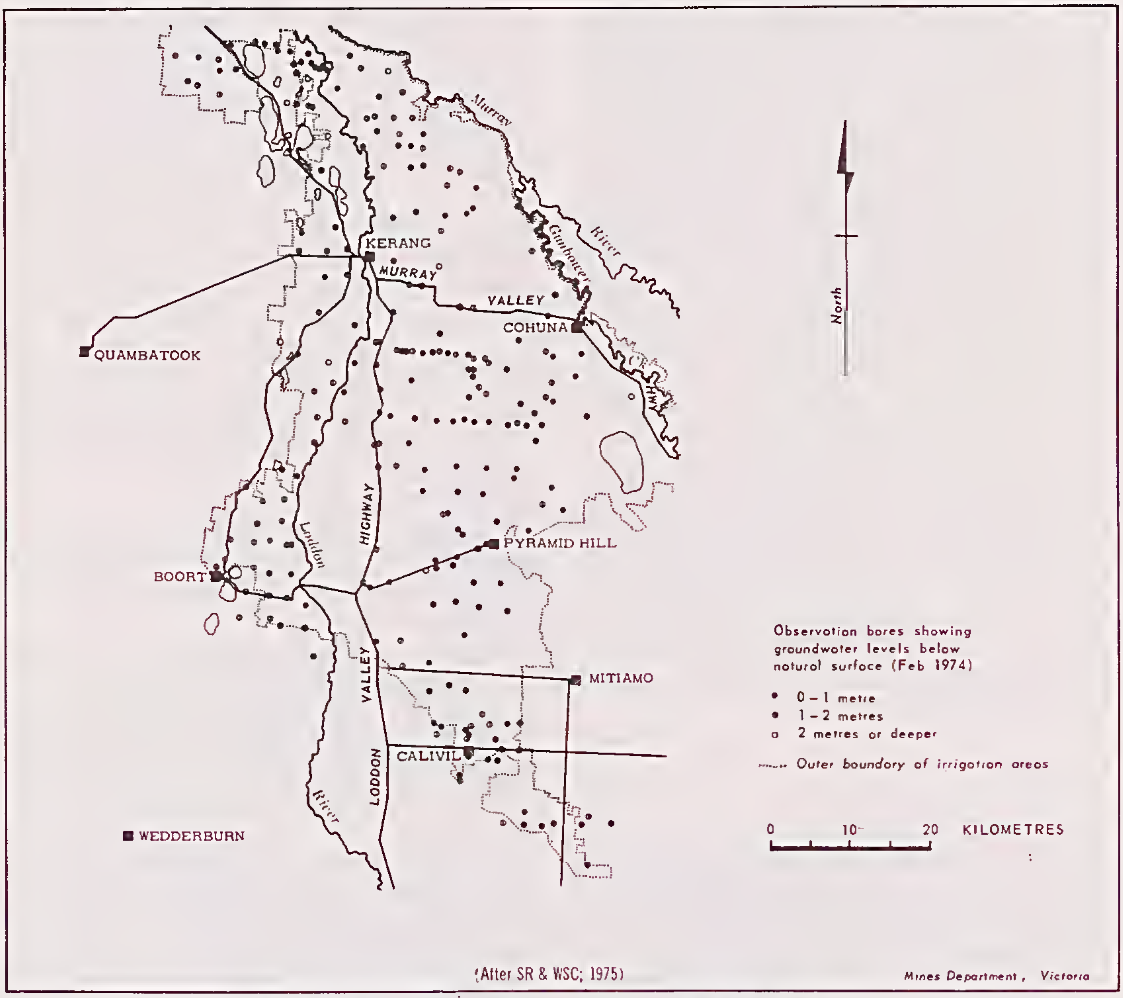

FIG. 3 — Kerang region watertable levels at Feb. 1974.

piezometric surface of the Calivil Formation becomes artesian, shows many of the discharge phenomena. For instance, about one third of the area in the mid-Loddon Plains has a high or very high salinity susceptibility with greater than 0.3% NaCl in the near surface soils. Further north most of the Plains have a very high susceptibility with greater than 0.5% NaCl (Skene 1971). Under pre-settlement conditions regional groundwater discharge took place by evapotranspiration by prior stream woodlands and phreatophytes, and by direct loss to rivers and lakes. The prior stream woodlands (Skene 1971) are best developed on levees of Pleistocene streams, the aquifers of which are in direct hydraulic connection with the more deeply buried regional aquifers. Prior stream woodlands are most common in the southern Loddon Plains, but on passing northwards give way to the treeless plain where phreatophytes were widespread prior to European settlement (Macumber 1978b).

Effluent lakes are scattered over the Loddon Plains, and in certain salinas, e.g. Lake Kelly, salt was once regularly harvested. While lakes like Lake Kelly are fed solely by groundwater, other lakes have both a groundwater and surface water inflow, the latter occurring during phases of high stream flow and sheet flooding. During such times the lakes are flushed of their more saline groundwater component. Typical is Lake Wandella, a permanent saline lake near Kerang, where piezometers show a general upward decrease in aquifer pressures. Pressure levels in underlying Parilla Sand aquifer found at a depth ranging from 20 to 80 m are 1.25 m above that of the lake surface. The Parilla Sand is a marine down-basin continuation of the fluviatile Calivil Formation aquifer (see later).

This general picture is in line with observations of Meyboom (1966), who correlated many of the major areas of soil salinity in southwestern Saskatchewan with discharge areas of regional groundwater flow. However, while upward moving groundwater is a significant contributor to the high salinity of shallow water tables, the author has previously demonstrated that salt additions from various other sources have also contributed to the present high salt status of the Loddon Plain (Macumber 1968).

Piezometric Observations

On its course across the Loddon Plain the deep lead valley is cut into Palaeozoic basement except between the parishes of Pompapiel and Mologa. Here it is incised into lower-middle Tertiary Renmark Beds. However, even where the Calivil Formation does not form the basal aquifer, the relatively low permeability of the underlying Renmark Beds means that for all practical purposes the Calivil Formation may still be regarded as the basal aquifer. Furthermore, since the permeability of the Calivil Formation is orders of magnitude greater than the overlying sediments, its potentiometric surface can be meaningfully mapped (cf. Freeze 1969, p. 4).

The potentiometric surface of the Calivil Formation obtained before 1973 was based on some dozens of bores along the infilled lead valley. Its shape was a parabolic curve, some 24 m below the surface at Laanecoorie but rising to only 12.5 m down at Bridgewater; it was artesian (flowing) for low lying bores at Calivil, beyond which point bores either flow or may be considered as existing in an artesian transition zone (see Fig. 6).

In the transition zone, the potentiometric level of the Calivil Formation is within 2 m of the ground surface. The minor fluctuations in topography in this very flat region are sufficient to determine whether or not a bore will flow. Thus the permeable sandy soils developed on the elevated levees of the prior stream system near Calivil are not greatly affected by shallow saline water tables present under the adjacent plain, and are therefore regarded as superior irrigation areas. Bores on the levees intersecting the Calivil Formation do not flow, whereas bores on the plain are artesian. Indeed, the difference in elevation is sufficient for the development of a first order flow system, with irrigation recharge of the permeable levee soils leading to groundwater discharge via capillarity on the adjacent plains.

Climatic Influence

The 1968 program established a series of observation bores to monitor the fluctuations in the deep groundwater system. Permanent Leopold-Stevens water level recorders were established on bores as they were drilled, and those not so equipped were monitored monthly. Nine observation bores are established over the main deep lead valley between Bridgewater and South Cohuna.

Before 1973 a regular seasonal pattern of minor fluctuations in pressure levels was recorded, with a slight drop over the summer months and a similar rise in winter. The total amplitude of the fluctuation over a four year period was only 0.6 m, peaking in late winter (Fig. 4). During 1973-74 anomalously high rainfalls were experienced in the catchments (Tables 3 & 4) and the plains were subjected to sheet flooding via the distributary

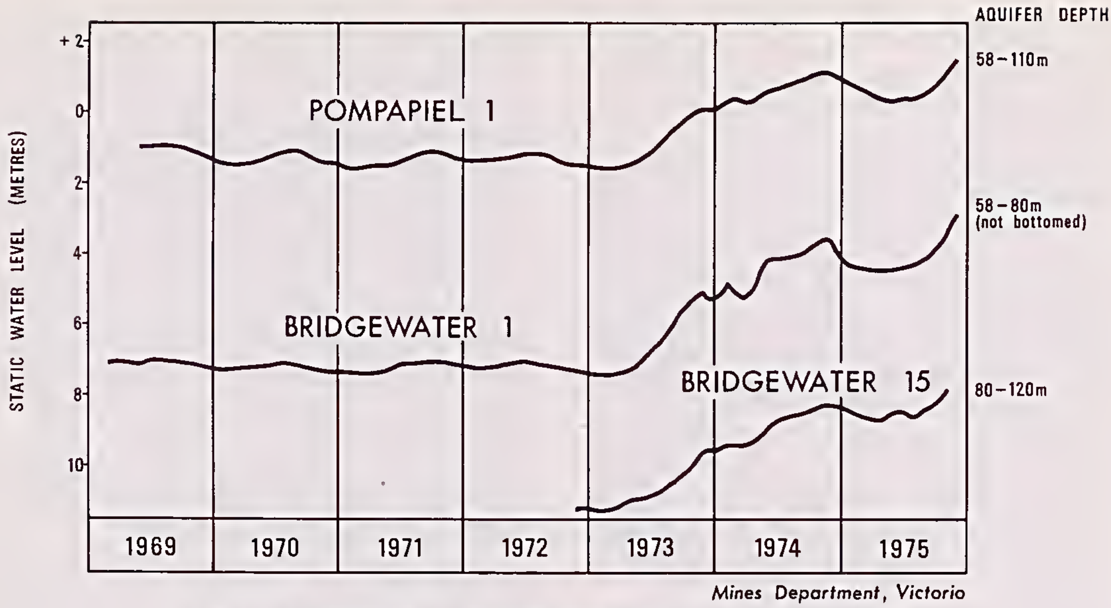

FIG. 4 — Hydrograph of the static water levels — Calivil Formation.

TABLE 2

PRECIPITATION AT SELECTED STATIONS (mm)

Station	*1973*	*Mean*	*% Increase*
Ballarat	958	713	34
Boort	878	389	126
Maryborough	1022	518	97
Bendigo	1017	549	85

systems of the Loddon River and Serpentine Creek, and by Bullock Creek (Fig. 5).

In Autumn 1973, the pressure levels of the Calivil Formation began to rise and by early winter they had surpassed the highest levels reached during the four previous years; they continued to rise throughout the remainder of 1973 and peaked in late spring 1974. The rise was 3.5 m at Bridgewater, 3.7 m at Yarrayne and 2.8 m at Pompapiel (see Fig. 4). As a result of the rising pressures, bores from Pompapiel to Calivil began to flow for the first time since observations were begun, the observation bore at Pompapiel rising to 1.10 m above the natural surface.

The wet period of 1973-74 was followed by an abnormally wet spring in 1975, with further sheet flooding of the plains. Pressure levels again rose, but from a base level well above that of the pre-1973 period. In all bores on the southern plains the previous peaks had been surpassed by mid-October. The Pompapiel No. 1 static level had by November reached a point some 1.5 m above the surface. New levels at Bridgewater No. 1 bore were only 3.7 m below the surface, a rise of 4.5 m over the levels of early 1973.

Since the most southerly artesian bore up to 1973 had been at Calivil, the flowing bore at Pompapiel showed that the point at which the lead system had become artesian had moved upgradient a distance of over 20 km (Fig. 6). In this new position the aquifer is overlain not by the lower permeability aquiclude as at Calivil but by a significantly more permeable aquitard. Indeed at Bridgewater the sediments overlying the Calivil Formation are

TABLE 3

STREAM FLOW IN THE LODDON RIVER AND TRIBUTARIES

Stream	*Discharge 1973 (Ml)*	*Mean Annual Discharge (Ml)*	*Discharge 1956 (Previous Peak flow) (Ml)*
Bet Bet Ct at Norwood	6.8×10^4	1.7×10^3	4.9×10^3
Tullaroop Ck at Clunes	1.2×10^5	6.1×10^4	1.7×10^5
Loddon River at Laanecoorie	1.5×10^6	2.5×10^5	8.1×10^5
Loddon River at Appin	3.0×10^5	1.0×10^5	3.0×10^5

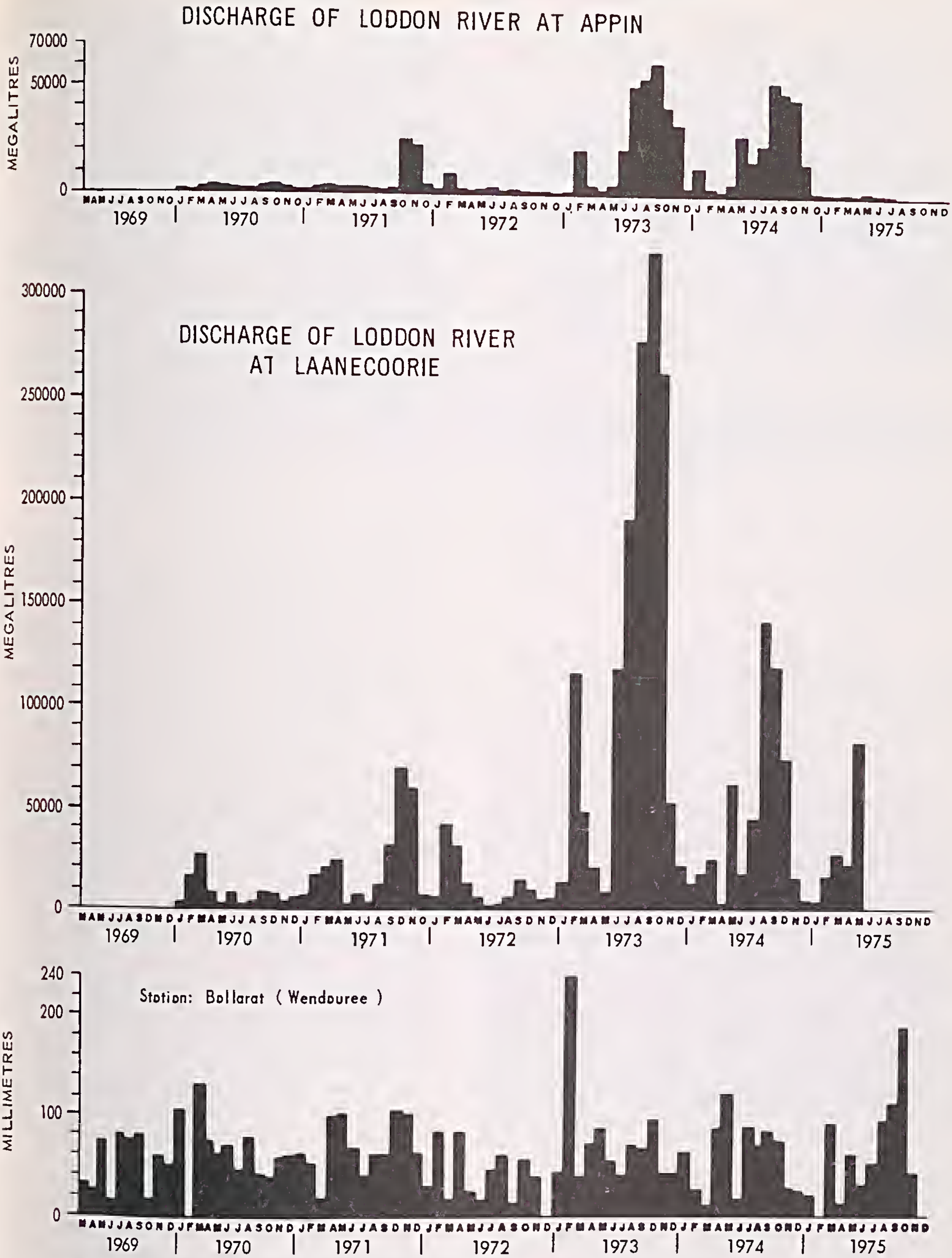

FIG. 5 — Rainfall in the Loddon River catchment, and Loddon River discharges at Laanecoorie and Appin 1969 to 1975.

TABLE 4

EXAMPLES OF LOW SALINITY WATERS IN THE UPPER LODDON PLAINS

Bore No.	TDS (mg/l)	$HCO_3+CO_3/$ $Cl+SO_4$ (% me/l)	Depth (m)
Yarraberb 15	191	0.7	18.3-24.4
Yarrayne 10002	228	1.03	5.5- 7.6
Yarrayne 10002	368	1.06	29.0
Yarrayne 8	372	0.86	24.1-24.7
Yarraberb 14	475	0.82	24.4
Yarraberb 9	480	1.04	17.7-26.2
Yarraberb 14	595	0.85	25.3

For comparison an average figure for the Calivil Formation aquifer in the Parish of Yarraberb is given.

Bore No.	TDS	$HCO_3+CO_3/$ $Cl+SO_4$	Depth
Yarraberb 8007 (L. Dickens)	1223	0.35	65.3

moderately permeable and present only nominal vertical hydraulic resistance. The aquifer is seen as being semi-confined to semi-unconfined.

Upstream from Bridgewater the aquifer system is confined by basalt flows; downstream at Calivil it is overlain by clays. Therefore the higher permeabilities of the aquitard between Bridgewater and Calivil provide an escape valve for pressure build up in the Calivil Formation. During phases of high pressure levels as in 1973-75, the basal aquifer becomes artesian within this area with resultant net upflow into the overlying shallow shoe-string sands. The transmission of water along devious pathways of randomly criss-crossing shoe-string sands spreads the area over which groundwater discharge occurs well beyond the lateral limits of the deep lead valley. During the period of peak potentiometric levels in late 1975 situations were found where intermediate aquifers and even some shallow shoe-string sand systems less than 10 m deep became artesian. Direct hydraulic continuity was firmly established between the shallow system, intermediate system and Calivil Formation.

Shallow water tables and evidence of groundwater outcrop appeared in unirrigated areas that had previously been highly productive. Bears Lagoon, one of many local drainage lines, is incised 3 m below the plain, at a point only 0.2 km west of an area of groundwater outcrop in 1975 when pressure levels were at their highest. The lagoon receives groundwater seepage and salt effloresces along its banks. The local observation that the lagoon has on occasions carried water without any apparent surface source is seen as a groundwater discharge phenomenon. In July 1976, at the height of a severe drought, Bears Lagoon was a flowing effluent stream.

The direct distribution of pressure along the shoe-string aquifers influences the ultimate pressure levels of shallow systems in the middle and lower plains. Since the shallow aquifers are prior streams dying out on the plains they have a decreasing carrying capacity because of lower downstream transmissivities and widths. High pressure levels in the deep Calivil Formation must therefore lead to greatly increased rates of water loss from the shallow systems into the overlying clay layers on the middle and lower plains.

MOBILITY OF THE RECHARGE-DISCHARGE BOUNDARY

On the Loddon Plains the pressure level variations in the Calivil Formation are greatest in Bridgewater bore No. 1, in the Parish of Yarrayne (4.4 m over the period March '73 to November '75). These values fall off to the south and north where Bridgewater 14 and Pompapiel 1 have values of 3.3 and 3.1 m respectively. This decline continues northwards with a range of 0.2 m near Pyramid and 0.8 m at South Cohuna. It is noteworthy that the zone of greatest pressure fluctuation lies between Bridgewater and Pompapiel. With a static level some 1.5 m above surface level, the latter areas are clearly the zone of groundwater discharge. However upstream at Bridgewater, the static levels are sufficiently low to suggest that we have crossed the hinge-line out of the discharge zone. South of the hinge, the area comprising the parishes of Yarrayne and Yarraberb is one where two major surface systems, the Loddon River and Bullock Creek, emerge from their highland tracts onto the plains. It is in this area that the Loddon Fan begins (Macumber 1968), and where, in the early maps, Bullock Creek, which is well established further back within the highlands, is shown as dying out and re-appearing further downstream to become the Pyramid Creek.

It is noteworthy that this is the only area on the Loddon Plains where low salinity shallow groundwaters are found, albeit often in juxtaposition to higher salinity waters. Salinities are often well below 1000 mg/litre and reach as low as 200 mg/litre. The chemical character of these waters, in keeping with their low salinity, is unique

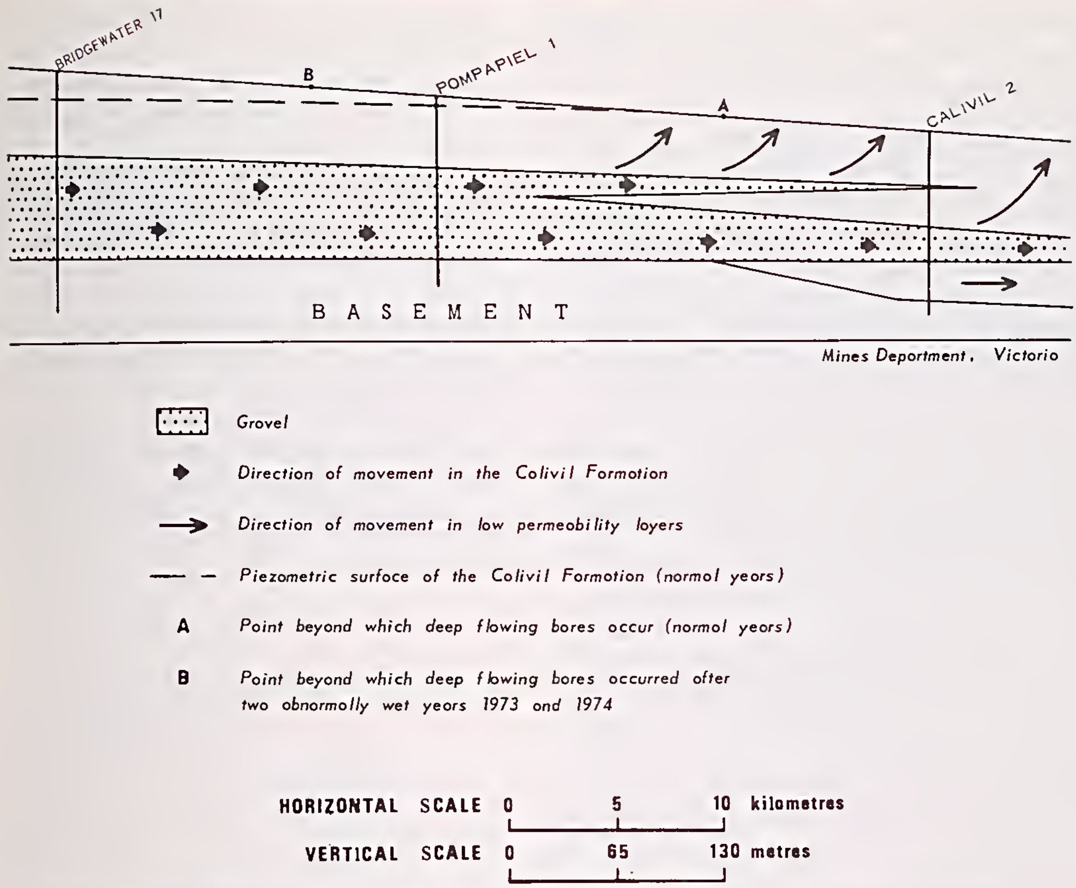

FIG. 6 — Hypothetical flow pattern in the sediments of the south-central Loddon Plain.

to the plains. They have relatively high HCO_3/Cl ratios which in some instances allow them to be categorized in the carbonate-chloride hydrofacies (Table 4). Local recharge is indicated. Therefore the hinge must lie between Yarrayne and Pompapiel. Moreover because of the sensitivity of the potentiometric surface to periodic short term climatic variations, the hinge-line must be considered as very mobile, moving within a zone 20 or more km wide in response to these climatic fluctuations.

REGIONAL EXTENSIONS

Lower Loddon Plains

In the central areas of the Loddon Plains, between Calivil and Macorna, the Calivil Formation is overlain by about 75 m of uniform, moderately dense clay. However after Macorna the Tertiary shore line is crossed; the Calivil Formation is thereafter directly overlain by the marine Parilla Sand. Between Cohuna and Kerang, the Parilla Sand comes to within 18 m of the surface. As on the central and upper Loddon Plains, the standing water level of the Calivil Formation is either at, or very close to, the surface.

Although the overlying units within the Parilla Sand are significantly less permeable than its basal units they would at the most be semi-confining and unlikely to provide much resistance to upward moving groundwater with a positive hydrostatic head. This too is the case for the Quaternary units overlying the Parilla Sand. Between Cohuna and Kerang, the Murray Plains are criss-crossed by a series of shoe-string sands associated with former courses of the ancestral Goulburn River (Macumber 1968, Macumber & Thorne 1975). The situation is therefore similar to that found on the southern Loddon Plains, where shoe-string sands have been shown to provide pathways for upwards moving groundwater. Lawrence (1976) regards this area as being within a groundwater discharge zone.

Riverine Plains to the East

The rapidity and extent to which the pressure levels in the Calivil Formation rose following the two abnormally wet years of 1973 and 1974 proves an unexpected degree of sensitivity in the deep groundwater regime to climatic fluctuation. Yet waterlogging and salinity problems are not restricted to the Loddon Plains. The rapid rise in aquifer pressures in the Loddon Valley was echoed in part by rises in pressure levels in shallow aquifers, and in the water tables, of the irrigation districts of the Campaspe and Goulburn valleys. This caused large scale losses of fruit trees by waterlogging and salinization (S.R. & W.S.C. 1975). A slow gradual rise in water tables as a result of irrigation had been previously recorded by the State Rivers and Water Supply Commission. However the onset of the wet years 1973 and 1974 led to a sudden dramatic rise in the water tables, and virtually overnight threatened the irrigation districts of the Campaspe and Goulburn valleys. Unlike the situation on the Loddon Plains, the Calivil Formation pressure levels are well below the surface and the hydrological changes are not as yet linked to the regional groundwater flow system. It nevertheless seems that the critical balance that exists between water budget and hydrologic equilibrium on the Loddon Plains is still a fairly acute problem in large areas of the Riverine Plains further east. On a regional scale, a fundamental shift in hydrologic equilibrium is occurring in the regional groundwater flow systems where pressure levels have been rising at a general uniform rate over the past 75 years. This will eventually result in the development of regional groundwater discharge zones on the Campaspe and Goulburn plains (Macumber 1978b).

PALAEOHYDROLOGICAL IMPLICATIONS

It is interesting to speculate on the effects of the late Quaternary periods of very much higher stream discharge than at present, which are well documented on the Riverine Plains (Pels 1966, Bowler 1967, Macumber 1968, Schumm 1968). There is some doubt as to whether the high discharges result from higher precipitation, from lower temperatures, or from both. All would lead to greater recharge of the regional groundwater flow systems.

Given the known response of the aquifer to short term climatic anomalies, the effects of similar events lasting several millennia or longer would have been very profound. Not only would pressure levels have been considerably greater, but more significantly the point at which the piezometric surface intersected the natural surface would have been pushed upstream to beyond Bridgewater, making the entire Loddon Plains an area of groundwater discharge.

Such effects on the hydrogeology of the plains would have been dramatic. Groundwater outcrop would have been a significant feeder to already overloaded surface systems. This is clearly seen in the case of Bears Lagoon which rises in, and drains, the area underlain by the high water tables of 1975 (see Fig 7). Its origin is seen to date back to a time of general high pressure levels and continuous groundwater discharge. This is almost certainly the origin of many of the small streamlet and drainage line traces now found criss-crossing the upper Loddon Plains.

Under extreme conditions of water logging the highly saline shallow water table would have been at the surface in the central lower plains, with the resultant destruction of vegetation. (At present 90% of the shallow groundwater has a salinity of greater

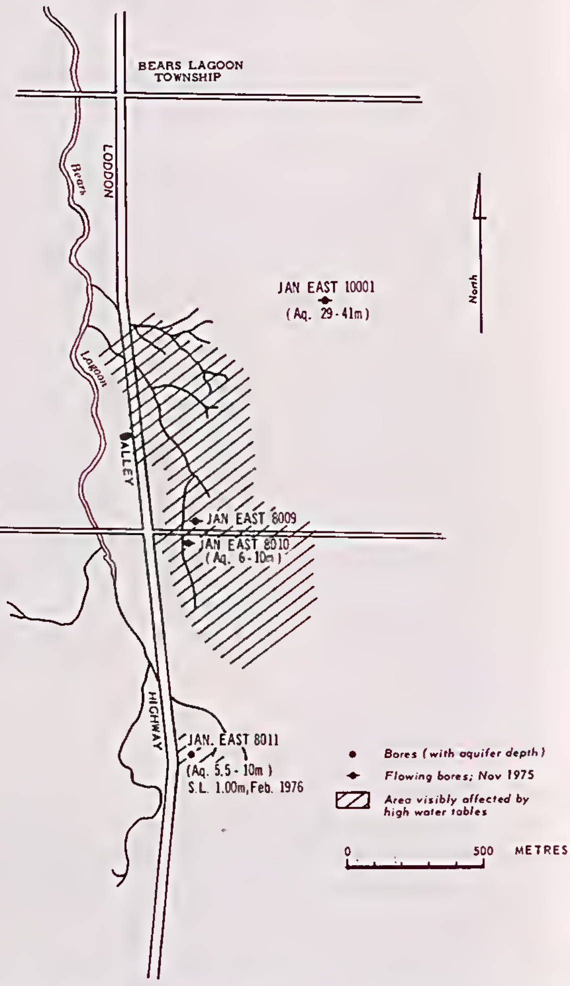

FIG. 7 — Groundwater discharge at Bears Lagoon, November 1975.

than 10,000 mg/litre and 40% is greater than 20,000 mg/l.) The lower-central Loddon Plains would have been a virtual saline swamp, with water loss by evaporation leading to ever-increasing salinity levels. This is in line with the observation that the geochemistry of the shallow saline waters varies little from that of the brackish and fresh waters of the surface systems and deep aquifers.

High water tables were in existence on the Loddon Plains as late as 9,000 years ago as shown by the Kow Swamp study (Macumber 1977). The re-appearance of eucalypts along stream courses and in shallow depressions on the plains at about 8,000 B.P. (Bowler 1968, Macumber 1977) can be interpreted as a response to the decline in regional water tables on the Riverine Plains in early Holocene time.

CONCLUSIONS

(1) The 'deep leads', late Tertiary gravels partially infilling the Loddon Valley, provide the major flow-path for groundwater moving plainwards from the highlands. On the Loddon Plains, hydrostatic forces cause the groundwater to move from the deep aquifer into overlying sediments and to the surface. Much of the Loddon Plain, therefore, lies within a groundwater discharge zone, and this is reflected in the high salt status of the soils and shallow groundwaters.

(2) This study indicates that on the Loddon Plain there is a ready interchange between the groundwater and surface water systems, both of which make up two aspects of a single integrated down-basin flow system.

(3) The high sensitivity of the groundwater system to a small increase in water budget indicates a delicately balanced hydrologic regime. For any full comprehension of the dynamics of the regime consideration must be given not only to the water budget, but also to basin geology and morphology. It demonstrates the need for management and research studies that integrate surface and groundwater hydrology.

(4) A model is provided for understanding the impending development of regional groundwater discharge conditions in other areas of the Riverine Plain. It thus opens the way for a new understanding of past erosional and depositional episodes controlled either by the emergence of discharge zones or by shifting hinge-line effects.

(5) Given an understanding of the structural and stratigraphic framework of the basin, and the dynamics operating within the flow systems, it is possible to gain an insight into the environmental effects that may have accompanied hydrologic changes of the Quaternary age.

ACKNOWLEDGMENTS

I thank Dr. D. Spencer-Jones, Director of Geological Survey, Victoria, for permission to undertake this program, and Mr. W. A. Esplan for his continued encouragement during the course of the investigation. Mr. B. Thompson critically read the manuscript. Mr. G. Jones, Victorian Department of Agriculture, first brought the high water table conditions at Bears Lagoon to my attention.

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